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AN EXPLORATORY SIMULATOR STUDY ON THE USE OF ACTIVE CONTROL DEVICES IN CAR DRIVING

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Title:	An exploratory simulator study on the use of active control devices in car driving
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SUMMARY

The present study deals with the question whether at the handling level of car driving active control devices (i.e. active steering wheel, active gas-pedal) may serve as a part of an integrated, intelligent co-driver system, that may help the driver to behave safely and efficiently in tomorrow's traffic.

The experiment, which was carried out in the TNO driving simulator was devided into three blocks:

- a lateral control task (lane-change manoeuvre) supported by the active steering wheel,
- a longitudinal control task (speed control) supported by the active gas-pedal,
- a combined control task (lane-change manoeuvre and speed control) supported by both active controls.

Different force feedback characteristics for the active control devices served as the main independent variable. The results indicate that steering support may be fruitfully applied as a warning system preventing drivers to leave their lane. Furthermore, intelligent force feedback from the accelerator pedal appeared to be useful in speed-error reduction. Continuous force changes which are directly related to speed error seem most promising. Interference effects may occur in case of simultaneous presentation of vibrating signals on both steering wheel and accelerator. The present simulator findings need further verification in field studies.

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Instituut voor Zintuigfysiologie TNO
Soesterberg

Een verkennend simulatoronderzoek naar de bruikbaarheid van actieve bedieningsmiddelen in een auto

J. Schumann, J. Godthelp en W.H. Hoekstra

SAMENVATTING

Dit onderzoek behandelt de vraag op welke wijze zgn. actieve bedieningsmiddelen kunnen worden toegepast als integraal onderdeel van een driver-support systeem in een auto. In een experiment dat werd uitgevoerd in de TNO rijsimulator werden verschillende uitvoeringsvormen van een actief stuurwiel en een actief gaspedaal onderzocht. Het experiment omvatte drie blokken waarin verschillende rijtaken werden beschouwd:

I rijstrookwisseling met ondersteuning door stuurkrachtsignalen,

II snelheidsregeltaak met ondersteuning door tegenkracht vanuit het gaspedaal,

III combinatie van rijstrookwisseling en snelheidsregeltaak met ondersteuning door zowel stuurwiel- als gaspedaalsignalen.

Tijdens het experiment werden verschillende systemen van krachtterugkoppeling voor zowel het stuurwiel als het gaspedaal vergeleken. De resultaten geven aan dat beide vormen van terugkoppeling zinvol kunnen zijn. Een korte tegenkracht op het stuurwiel vormt een bruikbaar waarschuwingssysteem ter voorkoming van het uit de rijstrook raken. Snelheidsgedrag kan worden verbeterd door het geven van krachtterugkoppeling op het pedaal, welke direct gekoppeld is aan de snelheidsfout. Bij gebruik van korte vibraties als waarschuwingsvorm blijken interferentie-effecten op te treden indien dergelijke signalen tegelijkertijd via stuurwiel en gaspedaal worden aangeboden. De bevindingen van dit onderzoek behoeven nadere verificatie in een veldstudie.

1 INTRODUCTION

One of the challenges con...: .d with the use of modern communication and information technology in ro'. traffic is the development of a so called "co-driver" system. Whereas in airplanes the use of smart sensors, fly-by-wire systems and intelligent failure detection and identification methods has become quite common, the lack of using these modern techniques in automobile control becomes more and more visible. Given the unsafety and pollution figures related to road traffic one could even suggest that conventional techniques have dominated land traffic technology far too long. Recent European research programs as PROMETHEUS and DRIVE have recognized this situation and initiated a series of projects which aim to develop knowledge and techniques that may help to regain control over road traffic in Western European countries. The GIDS-project is one of the DRIVE-projects (GIDS = Generic Intelligent Driver Support Systems). Its main objective is to develop requirements for an intelligent co-driver system, that may help the driver to behave safely and efficiently in tomorrow's traffic (Smiley & Michon, 1989). In its earliest form, GIDS will involve a dialogue system which supervises and presents navigation, anti-collision, and vehicle control information in an "user-friendly" way. One of the major subgoals of GIDS is to reduce driver workload in critical traffic conditions. Several important research issues are included in the GIDS-project:

- Development of technical sensors and communication systems which might provide adequate information to the GIDS system.
- Making available existing and newly developed knowledge about the driver's needs in critical driving situations; making the GIDS system adaptive to changes in driver needs as effected by experience, knowledge, etc.
- The design of an optimal interface which provides the driver with GIDS information in a suitable manner, i.e. spatially and temporarily balanced in relation to the user's capabilities and needs.

The present study deals with the last research issue and focusses on the question whether active control devices (i.e. an active accelerator and an active steering wheel) may serve at the handling level of car driving (see e.g. Johannsen, 1990) as an element in an integrated information system in a future GIDS car. The idea behind the use of active controls is to reduce driver workload by using the control devices (accelerator, steering wheel) not only as control device but also as an information system to the driver.

Active control devices convey relevant information of the controlled system to the driver and therefore concurrently serve as a proprioceptive-tactual display (Rühmann, 1981). The term "tactual" is used in the meaning of Schiff and Foulke's (1982) definition in "...referring to active exploratory and manipulative touch". The tactual sensation mainly consists of touch, pressure, and vibration transmitted by different cutaneous sensory receptors (Sherrick & Craig, 1982). Through the action of the limbs the proprioceptors - sense organs in the subcutaneous tissues of muscles, tendons, and joints - are activated simultaneously (see

Geldard, 1972). From an information processing perspective the employing of active controls is described within the concept of stimulus-response compatibility (Sheridan & Ferrell, 1974; Wickens, 1984), since the receptors of the information synchronously serve as effectors for an action proposed by the stimulus information. According to Sanders and McCormick (1987) compatibility links the relationship of stimulus and response to the driver's expectation and therefore can result in a reduced workload, faster response times, and fewer errors. Massaro (1990) terms this relationship "perceiving-acting" compatibility, which will be supported by an active control device. Moreover, an active control can offer a meaningful interaction with the environment which helps to build up effective functional units of activity and facilitates a compatibility matching, i.e. the assembling of intended driving control actions on the basis of displayed proprioceptive-tactual cues (see common coding approach in information processing, Prinz, 1990). The control loop for an active control device is shown in Fig. 1. In automobile driving the accelerator and steering wheel can be used as active control devices for longitudinal and lateral control respectively.

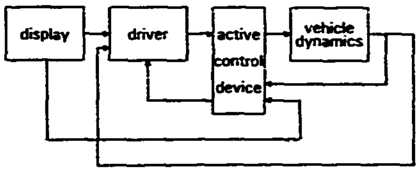

Fig. 1 Schematic diagram of the control loop with an active control device.

1.1 The use of an active accelerator for speed control

Many road accidents happen because one drives too fast. Entering a sharp bend, driving through a village while misjudging one's own speed, following a high speed leading vehicle, etc., these are all examples of every day driving, which may result in dramatic consequences. During the last two decades most European countries developed various kinds of speed measures. Millions of Ecu's were spent in order to drastically change the geometrical design of city and village streets as measures to force the car driver to reduce speed. In addition, Rutley (1975) already suggested the clever use of advisory speed signs, carriageway markings and even head-up display speedometers to influence driver speed. The success of enforcement and of all of these technical solutions has appeared to be rather limited in each case. Tenkink (1988) analyzed the effectiveness of speed reducing measures and concluded that they only will be effective when, 1) the user population considers them as logical, and 2) the measure has verifiable negative consequences in case of neglecting. Furthermore, a disadvantage of most of the regular speed reducing measures (signs, road design) is that they are

most of the regular speed reducing measures (signs, road design) is that they are permanent and non-adaptive to the local/momentaneous traffic situations, e.g. a 30 km/h limit may be acceptable during peak- hours near a school-area. However, at the same place a 60 km/h limit may be sufficient at 11 o'clock in the evening. Such an adaptability of elementary traffic rules seems of high importance for their acceptance (Oei & Papendrecht, 1989). Given these limitations of conventional speed reducing measures several authors recently wondered why such a small research effort has been put in the development of adaptive speed limiters or warning systems that operate inside the car. Echterhoff (1985) investigated the acceptability of such speed limitation systems. Subjects drove a car which automatically adapted its maximum speed to the local speed limit. They were quite positive about this device and argued that they would accept it "provided that everybody would use such a system". In a similar study Malaterre and Saad (1984) found that when only a limited number of cars is provided with such a speed limiter, other traffic participants may react unprepared, which may cause unwanted behaviour. However, to consider this result as a negative aspect of such a speed reducing measure seems not appropriate. Together with headway regulation, speed control serves as an important element of a so-called intelligent cruise control, which is meant to harmonize traffic streams. When evaluating the usefulness of different types of Road Transport Informatics the effectiveness of speed regulating devices is often estimated as to be enormous (Marburger, Klöckner & Stöcker, 1990). In its present form the accelerator hardly provides any systematic proprioceptive- tactual feedback to the driver about the momentaneous speed or headway of the car. Yet the workload reduction provided by information cues conveyed through non-visual and non-auditory sensory modalities, e.g. via kinesthetic information from a manipulator has been demonstrated repeatedly in aircraft-control (Merhav & Ben Ya'acov, 1976; Hosman & Van der Vaart, 1988). Fig. 2 shows the principle of an active side-stick controller as tested by Hosman and Van der Vaart (1988). The pilot force is used to control the aircraft, whereas the side-stick position is artificially connected to the aircraft roll angle (or in another test condition to the roll rate). From a series of experiments it appeared that these types of position feedback may serve as a very efficient cue to the pilot.

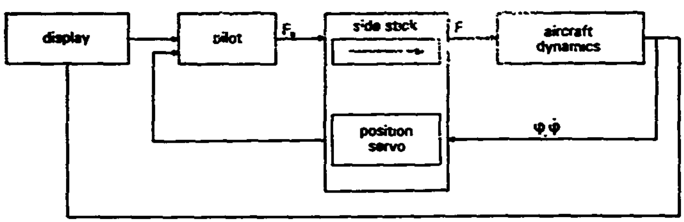

Fig. 2 Control loop with a servo-controlled side stick as an active controller, with roll angle φ, roll rate $\dot{\varphi}$ (Hosman & Van der Vaart, 1988).

When developing an active accelerator as an integrated element in a GIDS system, the control loop of Fig. 3 is proposed. Given the limited position range of an accelerator the pedal-force is chosen as an information-carrier to start with.

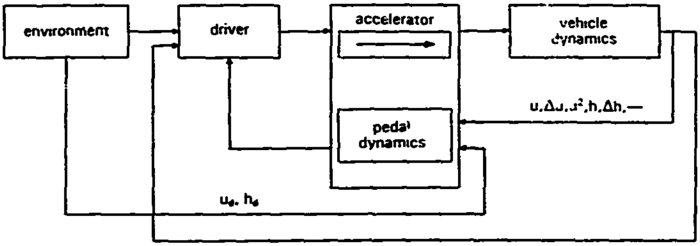

Fig. 3 Schematic diagram of the man-vehicle control loop with an active accelerator providing proprioceptive-tactual feedback about the error between the actual situation and a given normative behaviour model.

The schematic diagram of the system indicates that several speed or headway related dimensions can be fed back as a force cue, i.e. the force level can be chosen in correspondence with the momentaneous speed error (Δu) or headway error (Δh), etc.

With respect to both speed and headway, several functions can be given to such an active accelerator, i.e.:

- To provide proprioceptive-tactual information about speed or headway errors as compared to a given normative safety model.
- To serve as a speed or headway limiter by making the pedal force more or less infinite as soon as a speed limit is reached.
- To function as a speed regulation device providing force feedback based on a normative model which is related to fuel savings or pollution minimizing.

At a first stage in the process of specifying the feedback requirements of an active accelerator, a prototype of such a device has been developed for experiments in the TNO driving simulator. The potential effects of different pedal-force feedback characteristics were demonstrated in two explorative experiments (Färber, Färber, Godthelp & Schumann, 1990).

1.2 The use of an active steering wheel for lateral control

At the handling level of car driving the steering wheel is utilized for lateral control. Within an action-theoretic model of behaviour stabilization and steering

tasks are performed by the driver on a partly automated sensorimotor level of control (Rasmussen, 1986). Signals having a direct impact onto this level therefore can be transmitted by proprioceptive-tactual sensory modalities. According to Cruse, Dean, Heuer and Schmidt (1990) proprioceptive-tactual cues as sensory input for motor control can be used as feedback or reference signals for selecting motor programs and for elicitating movement. The employment of active controls, transmitting feedback via these sensory channels, has been put forward mainly in aviation (see e.g. Gilson & Fenton, 1972; Jagacinski, Flach & Gilson, 1983). Surprisingly, there have been made only sporadic attempts to use them in automobiles. Only recently, through the implementation of computer technology into an automobile, e.g. the design of "drive-by-wire" steering, active control technology is also under consideration in motor vehicle control. Hess and Modjtahedzadeh (1990) indicate that the steering wheel may convey feedback concerning lateral control performance to the driver and consequently may serve as a proprioceptive-tactual display. Sanders and McCormick (1987) argue that such a tactual display may have the advantage of utilizing a different sensory modality which can result in less competition for information processing resources (see also Färber et al., 1990). A disadvantage of tactual displays may be the need of a permanent contact between the hand(s) and such an active control device. However, in driving, such a permanent contact is expected to be assured in the case of steering.

Proprioceptive-tactual feedback information may be employed in different ways during the lateral control activities of the driving task:

- during closed-loop control, in supporting information from other sensory modalities (e.g. visual, auditory) in the meaning of redundancy gain and/or as visual workload relief,
- during open-loop control (mainly without visual feedback), in breaking up open-loop control and transferring it to closed-loop control.

In order to provide these types of feedback via the steering wheel, specific steering torque signals have to be developed. As such these signals should be functionally related to feedback cues which are used by the driver in regular vehicle control.

Two vehicle motion characteristics - the lateral position y and the heading angle ψ, which is proportional to the lateral speed $\dot{y}$ - serve as the driver's major visual input for the lateral control task (Carson & Wierwille, 1978). From these variables the TLC-measure (Time to Line Crossing) has been derived, representing the time necessary for the vehicle to reach either the left or right edge of the lane (Godthelp, Milgram & Blaauw, 1984). The control loop for an active steering wheel supporting lateral control is depicted in Fig. 4.

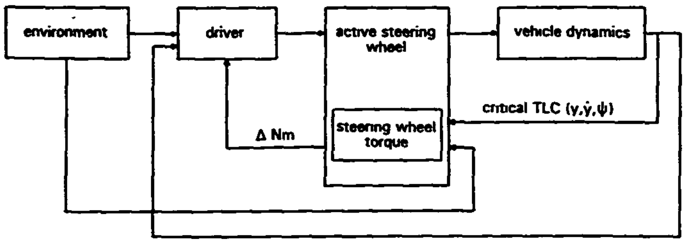

Fig. 4 Schematic diagram of the man-vehicle control loop with an active steering wheel providing proprioceptive-tactual feedback about the error between the actual lateral position and some normative behaviour (operationalized by a TLC-measure).

Proprioceptive information about lane exceedance via the active steering wheel has to enable the driver to react immediately and to correct his lateral deviation of the road course. Information will be provided by changing the steering wheel torque. This torque change may lead to critical situations during driving, if e.g. a sudden, strong torque change causes the driver to a startle reaction and to overpull the steering wheel. Therefore Schumann, Färber and Wontorra (1991) conducted psychophysical threshold experiments to determine small torque changes that are perceivable at the steering wheel by the driver. The level of these steering wheel torque shifts serves as a basis for the shaping of different steering wheel signals in the present study.

1.3 Research questions

The present study focusses on the overall question whether active control devices support the driver in his/her longitudinal and lateral control task.
Specifically, this was divided into several research questions:

- concerning an active accelerator: which force feedback characteristics will be most appropriate for driver support in speed regulation?
- concerning an active steering wheel: what proprioceptive-tactual signal characteristic is most sufficient in supporting the driver's lateral control task?
- concerning both active control devices simultaneously activated: are interferences to be expected for the longitudinal and lateral control task?

2 METHOD

2.1 General

The experiment was carried out in the fixed base driving simulator of the TNO Institute for Perception. This simulator involves a Volvo 240 mock-up, with regular steering wheel and pedals. The steering wheel axis is connected with a potentiometer which measures the steering wheel angle. Steering force is generated by means of an electric torque motor (Axem MV 19), mounted in the steering axis. In a similar way the accelerator position is measured by way of a potentiometer connected to the pedal-rotation axis, whereas the accelerator force feedback can be regulated by a torque motor (Axem F12 M2) which is connected to the pedal-axis by a gearbelt drive. The perspective view of the outline of the road was electronically generated by an Evans & Sutherland PS300 vector scan system and projected in front of the mock-up with a horizontal field of view of 50°.

2.1.1 *Subjects*

Eight male subjects (Ss) participated in the experiment, all of them had previous experience with the driving simulator. All Ss had their driving license for at least five years with a driving experience of at least 10000 km per year. Age varied between 23 and 38 years. They were paid for their services.

2.1.2 *Experimental conditions*

In the driving simulator subjects performed a speed adaption task (longitudinal control) combined with a lane-change manoeuvre (lateral control).
The whole experiment was devided into three blocks, i.e. I, II, and III, with only active steering support (I), only active speed support (II), and a combination of both active control devices (III), respectively.
Subjects participated on two successive days, starting on the first day with either block I or block II, wheras on the second day always block III with both active control devices was conducted. The order of the blocks I and II was changed for half the subjects.
In a within-subjects design, Ss participated in the three blocks of different support systems, i.e. I, II, and III. Within each block there were four sessions of different warning signals (see § 2.2-2.4). The order of the signals was presented according to a digram-balanced 4*4 Latin-square (see Wagenaar, 1969). Due to technical problems only seven subjects could participate in block II and III.
At the beginning each subject got a written instruction about the experiment. After a short introduction by the experimenter S took a seat in the mock-up. The experimenter always informed the subject about a change in the experimental conditions.

2.2 Block I: Lateral control task

2.2.1 *Task and stimuli*

The driver had to perform a lane-change manoeuvre on a two-lane rural road as depicted in Fig. 5.

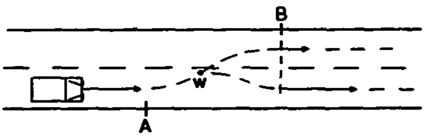

Fig. 5 Path of the lane-change manoeuvre, with and without warning (A: start of lane changing, B: lane barricade).

The driver started in the right lane at a predetermined fixed speed (100, 80 or 60 km/h). At point A (see Fig. 5) the driver had to initiate a lane-change manoeuvre to the left lane. The position of point A, which was always located at seven seconds before B, was indicated to the driver by occluding the visual scene for a short (0.5 s) period. After initiating the manoeuvre two conditions could occur:

- a *"without occlusion"* period, where S could perform the lane-change manoeuvre with complete vision,
- a *"with occlusion"* period, where the visual scene stayed occluded for additionally 2.5 s.

In most of the runs the lane-change manoeuvre could be carried out without problems, i.e. with a lane closure becoming visible in the right lane. However, in one third of the runs S was warned at point W (see Fig. 5) *not* to leave the right lane, i.e. to return to the centre of the right lane, because of the "sudden" occurrence of a lane barricade in the left lane. Point W was situated at a TLC distance of 2 s from the centre line. As described earlier, TLC represents the Time-to-Line-Crossing, i.e. the time until the left fender of the car would cross the center line. At 1.5 s after W the lane barricade became visible at the corresponding closed lane for that particular run. After point B the subject had to drive for three more seconds in his respective lane. Different warning signals at W were applied to indicate the driver to stay in the right lane (see Table I).

Table I Warning signals given at W to indicate the driver to keep the right lane.

Signal	Characteristic
auditory signal 0	short (0.5 s) tone
tactual signal 1	implemented at the steering wheel as a short (0.5 s) vibrating (10 Hz) torque shift (level 1.2 Nm)
tactual signal 2	implemented at the steering wheel as a vibrating (10 Hz) torque shift (level 1.2 Nm) continuously on, until lateral speed to the right ≥ 1 m/s.
tactual signal 3	implemented at the steering wheel as a short (0.5 s) steady torque shift to the right (level 2.4 Nm). See Fig. 6 for an exact characterization.

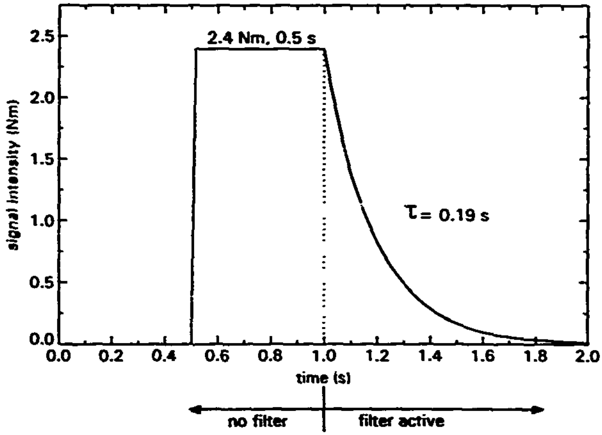

Fig. 6 Implementation of the steady torque shift to the right with an employed filter (τ = 0.19 s) for the down slope only.

2.2.2 *Procedure*

In block I each subject made four sessions of runs, each with one of the four different warning signals respectively. A session lasted about 30 minutes with a special training period to begin with. After each session subjects alternated, giving each subject a break for about 30 minutes between each session.

Training period

The training for the first session of warning signals consisted of 39 runs. It started with 13 runs of the lowest speed (60 km/h) of which the first seven runs were without occlusion (first four runs without a warning), followed by six runs with occlusion (first three runs without a warning). After that, 13 runs with each of the higher speeds (80 km/h and 100 km/h, respectively) were presented. The training for the next sessions of warning signals consisted only of 12 runs each (speed in ascending order; two runs with warning signals without occlusion, two runs with warning signals with occlusion).

Experimental session

In each session S made 54 runs, i.e. three sets of 18 runs with a constant speed of either 60, 80 or 100 km/h. The sequence of speed sets was randomized. In a set the first nine runs were without occlusion, to acquaint the driver to the steering actions for his lane-changing manoeuvre. In three randomly c sen runs a warning signal was assigned to indicate the subject to stay in the right lane. In the following nine runs with occlusion again three runs occurred with a warning.

2.2.3 *Data analysis*

Data storage started at point A with a sampling rate of 10 Hz. The following signals were recorded (see Fig. 7):

δ_s steering wheel angle
y lateral position
OCC occlusion
SF steering force
tw time instant of warning
ψ heading angle

From these signals the subsequent measures were calculated:

δ_{sl} maximum steering-wheel angle to the left
$\dot{\delta}_{sl}$ maximum steering-wheel velocity to the left
δ_{sr} maximum steering-wheel angle to the right
$\dot{\delta}_{sr}$ maximum steering-wheel velocity to the right
$|\dot{\delta}_s|_{3\text{-}7}$ mean absolute steering-wheel velocity between time instant 3 (occlusion ends) and time instant 7 (passing the barricade at point B).
$|\dot{\delta}_s|_{7\text{-}10}$ mean absolute steering-wheel velocity between time instant 7 (passing the barricade at point B) and time instant 10 (end of the run).
y_{min} minimal lateral distance to the center line
rt response time to warning signal, operationalized at a steering angle deviation > 2°.

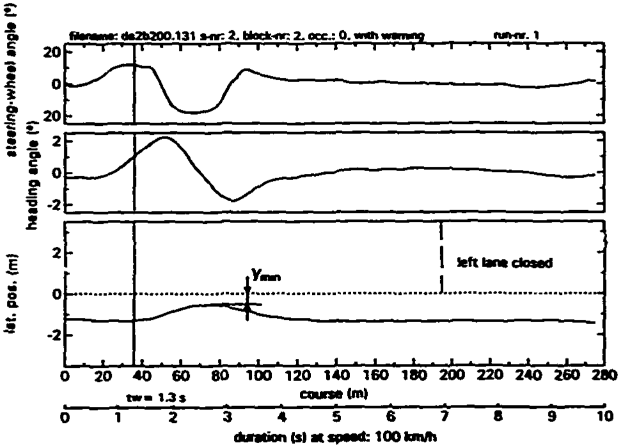

Fig. 7 Data storage for one experimental run (lateral position y, heading angle ψ, steering-wheel angle δ_s, time instant of warning tw).

Furthermore S was asked to fill in a questionnaire after each session of warning conditions.

Differences between warning conditions were tested by way of an analysis of variance (ANOVA, within-subjects design), which consisted of the following main factors: warning systems on four levels, speed on three levels, and occlusion (OCC) on two levels.

2.3 Block II: Longitudinal control task

2.3.1 *Task and stimuli*

Subjects' task consisted of driving on a two-lane rural road with a speed of 100 km/h. Drivers started in the right lane and approached a lane barricade at B (see Fig. 8). At a predetermined point A (7 s before B, except gas pedal signal 3, see below) the speed of 100 km/h should be stable (± 5 km/h), otherwise the run was stopped and started over again. At the moment of passing location A the requested goal speed at B (100, 85, 70, or 55 km/h) was presented on the central part of the screen.

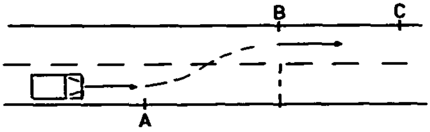

Fig. 8 Geometry of the manoeuvre path with the start of the lane change at A and the lane barricade and speed limit at B.

The appearance of the visual goal speed also served as a warning for the subject to change lanes, since the right lane was blocked at B (see Fig. 8). The barricade could easily be seen from A. After B the subject should stay in the left lane and keep the goal speed for a period of 10 seconds. To control the subject's looking behaviour with respect to the speedometer an occlusion device was installed:

- "*without occlusion*" is defined as a condition in which the speedometer is activated continuously until A has been reached, after which this information is only available on request for short (0.5 s) periods, i.e. by pressing the horn lever.
- "*with occlusion*" is defined as a condition in which the speedometer is activated continuously until A and not at all during the period A to B. After B the feedback via the speedometer is available again on request (0.5 s looks, see above).

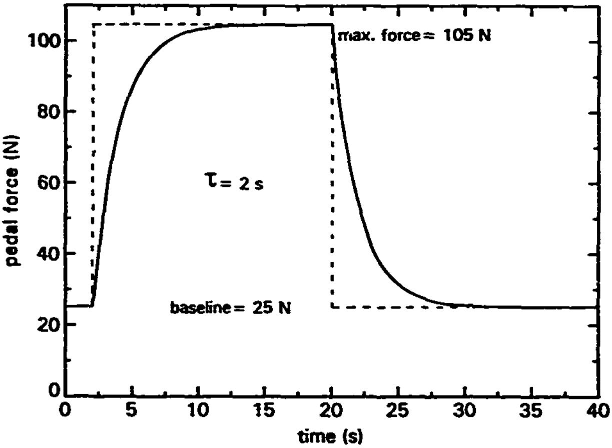

Fig. 9 Implementation of the discrete pedal position force feedback with a damping filter (τ = 2.0 s).

The conventional, "passive" accelerator was compared with three types of "active" pedal configurations. In each case the accelerator position s_g ranges from 0.0

(loosen) to 1.0 (full). The following force feedback characteristics were applied (see Table II).

Table II Warning signals and force characteristics of the accelerator.

Signal	Accelerator characteristic
visual signal 0	passive pedal (like PF5 force condition, Färber et al., 1990): $F_g = 10 + 50\, s_g$ (N).
active pedal 1	pedal force F_g depends on speed error: $F_g = 25 \pm 60\, u_e^2$ (N). Pedal force is limited at an upper and lower boundary of 250 N and 10 N respectively. Speed error u_e (m/s) is defined as the difference between the actual speed and the desired speed in the area after A. Desired speed is defined as a lineary decreasing function from the approach speed at A (100 km/h) to the requested goal speed at B.
active pedal 2	pedal force depends on pedal position, i.e. in relation to the pedal position belonging to the requested goal speed at B. $F_g = 25$ N, with $s_g \leq s_{g\ goal\ speed}$ $F_g = 25 + 80$ N, with $s_g > s_{g\ goal\ speed}$ This additional force is implemented with a damping filter with $\tau = 2$ s, see Fig. 9.
active pedal 3	pedal force as in case of passive pedal with the addition of a short vibration (0.5 s, 10 Hz, force amplitude 20 N) which is given only at point A. A is now located such, that releasing the gas pedal after the perceived vibrating signal leads to the correct goal speed at B (vehicle weight 1159 kg, driving in third gear). goal speed 85 km/h: A 113 m (4.1 s) before B goal speed 70 km/h: A 222 m (8.0 s) before B goal speed 55 km/h: A 318 m (11.4 s) before B

2.3.2 *Procedure*

Each S again made four sessions of runs, each with one of the four different accelerator characteristics respectively, the order of which was randomized. A session lasted about 30 minutes with a training period to begin with. After each session Ss alternated, giving each S a break of about half an hour between sessions.

Training period

The training for the first session of block II contained 32 runs. It started with eight runs of the highest goal speed (100 km/h). For the first four runs the speedometer could be activated after point A on request (no occlusion condition), for the following four runs the speedometer could be triggered for a short look only after point B (with occlusion condition). After that, the next lower goal speeds (85, 70, 55 km/h) were presented in the same sequence.
The training for the remaining three sessions of block II consisted only of four runs each (goal speed in descending order; two runs with no occlusion condition, two runs with occlusion condition).

Experimental session

In each session of block II S made four sets of eight runs. Sets alternated with respect to occlusion of the speedometer, starting with the no-occlusion set. Within a set the four different goal speeds were randomly presented twice.

2.3.3 *Data analysis*

Data storage started at point A with a sampling rate of 10 Hz. The following signals were recorded:

u	vehicle speed	m/s
obs	number of observations at speedometer	-
s_g	accelerator position	-
F_g	accelerator force	N
F_b	brake force	N

From these signals the following characteristics were derived:
u_e algebraic and absolute speed errors at location B and C
N_{obs} number of speedometer observations between A and B, and C

Differences between conditions were tested for statistical significance by way of an analysis of variance (ANOVA, within- subjects design), which contained the following factors: accelerator characteristics (ACC) on four levels, occlusion of speedometer (OCC) on two levels, goal speed on four levels, and replica.

2.4 Block III: Combined control task

2.4.1 *Task and stimuli*

In block III Ss had to perform a combination of the steering and speed control task of blocks I and II.
S started driving in the right lane and had to stabilize his speed at 100 km/h. At point A, which was located as in block II one of the four goal speeds was

presented on the screen. The active gas pedal supported the driver in reaching this speed. Seven seconds before B (like block I) occlusion started (either 0.5 or 3 s) to indicate the driver to change lanes. At a TLC of 2 s a warning via the active steering wheel could occur to inform the driver that he should stay within the right lane. 1.5 s after this TLC instant a lane barricade popped up at the corresponding closed lane. After passing this barricade the subject should stay in his lane for a period of 10 s and minimize speed error. The speedometer was activated continuously until A and not at all during the period between A and B. After B the speedometer could be actuated on request for a short look by pushing the horn lever (with occlusion condition from block II).
For the active steering wheel and the active gas pedal the following four signal combinations were employed (see Table III). These signals were chosen to compare a short and a continuous signal characteristic of each active control device.

Table III Four combinations of warning signals via the active control devices.

Active steering wheel	Active accelerator
short vibrating torque shift (tactual signal 1)	continuous speederror feedback (active pedal 1)
short vibrating torque shift (tactual signal 1)	short vibration at point A (active pedal 3)
cont. vibrating torque shift (tactual signal 3)	continuous speederror feedback (active pedal 1)
cont. vibrating torque shift (tactual signal 3)	short vibration at point A (active pedal 3)

Two short discrete signals (to initiate a control action) and two continuous signals (to support a control action) have been combined to compare conceivable interaction effects.

2.4.2 *Procedure*

Each S made four sessions of runs, each with one of the four different signal combinations for the active control devices respectively, the order of which was randomized. A session lasted about 30 minutes with a training period to begin with. After each session Ss alternated, giving each S a break of about half an hour between sessions.

Training period

The training for the first session of block III consisted of 18 runs. Six runs with the same goal speed (starting with 85 km/h, descending) were presented respectively. The first three runs were without occlusion (first run regular lane change to the left, then two runs with warning via the active steering wheel), the

remaining three runs included the three second occlusion period (same order as before).

The training for the other sessions of block III consisted of only nine runs with a warning via the active steering wheel (3 runs for each goal speed, starting with goal speed of 85 km/h with active gas pedal support, goal speed descending; only the respective first run being without occlusion).

Experimental session

In each session S made four sets of 12 runs with a constant goal speed (the sequence of the goal speed was randomized). Reaching the goal speed was supported by the active gas pedal. Each set started with six runs without occlusion. For three randomly chosen runs a warning was presented via the active steering wheel. In the remaining six runs with occlusion again three runs were with a warning via the active steering wheel.

2.4.3 *Data analysis*

Data storage started at point A with a sampling rate of 10 Hz. The following signals were recorded:

δ_s	steering wheel angle	
y	lateral position	
OCC	occlusion	
SF	steering force	
tw	time instant of warning	
ψ	heading angle	
u	vehicle speed	m/s
obs	number of observations at speedometer	-
s_g	accelerator position	-
F_g	accelerator force	N
F_b	brake force	N

From these signals the following characteristics were derived:

δ_{sl} maximum steering-wheel angle to the left

$\dot{\delta}_{sl}$ maximum steering-wheel velocity to the left

δ_{sr} maximum steering-wheel angle to the right

$\dot{\delta}_{sr}$ maximum steering-wheel velocity to the right

$|\dot{\delta}_s|_{3\text{-}7}$ mean absolute steering-wheel velocity between time instant 3 (occlusion ends) and time instant 7 (passing the barricade at point B).

$|\dot{\delta}_s|_{7\text{-}10}$ mean absolute steering-wheel velocity between time instant 7 (passing the barricade at point B) and time instant 10 (end of the run).

y_{min} minimal lateral distance to the center line

u_e algebraic and absolute speed errors at location B and C.

N_{obs} number of speedometer observations between A and B, and C.

Differences between conditions were tested for statistical significance by way of an analysis of variance (ANOVA, within-subjects design), which contained the following factors: combined warning signals on four levels, occlusion (OCC) on two levels, goal speed on four levels and replica.

3 RESULTS

3.1 Block I: Lateral control task

The ANOVA revealed no significant differences for the warning signals on the following measures:

- maximum steering wheel angle to the left and to the right,
- maximum steering wheel velocity to the left and to the right.

Also no significant differences were found in the mean absolute steering wheel velocity for the two defined areas after the warning signal.
This seems to indicate that, like an auditory warning signal, tactual warning signals via the steering wheel do not disturb the steering control actions.
There are, however, significant effects of the remaining two dependent variables, i.e. y_{min} (minimal lateral distance to the center line) and rt (response time to warning signal).
Fig. 10 shows the minimal lateral distance to the center line for the different warning signals.

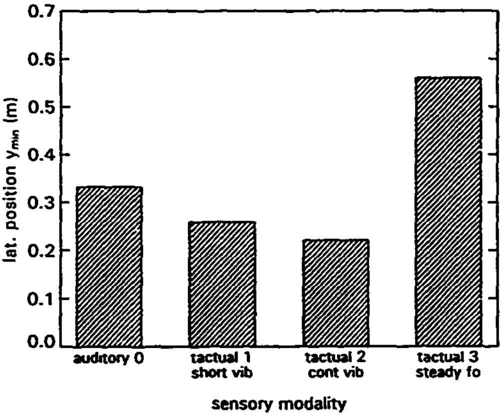

Fig. 10 Minimal lateral distance to the centre line for the different warning signals.

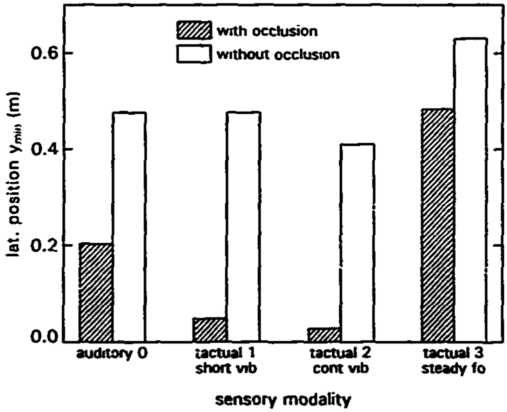

Fig. 11 Minimal lateral distance to the centre line for the different warning signals, with and without occlusion.

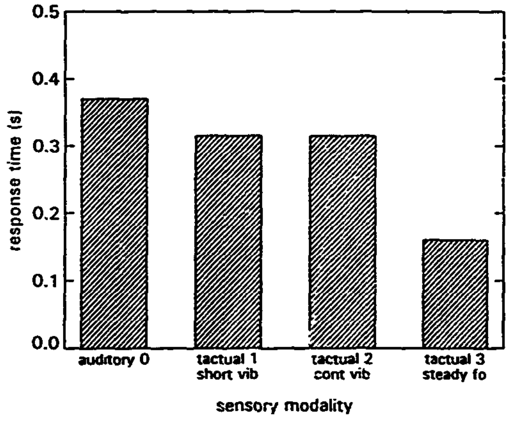

Fig. 12 Response time to the different warning signals.

The diagram reveals a significant effect of warning signals ($p < 0.01$). An additional contrast analysis, where each proprioceptive-tactual signal was compared with the auditory warning signal (as control condition) indicates that only the steady force warning signal (tactual signal 3) leads to a significant difference between pair of means ($p < 0.01$). The significant warning signal and

occlusion ($p < 0.05$) interaction is shown in Fig. 11. A post-hoc analysis (Tukey HSD test, see Kirk, 1982) shows significant differences between pair of means ($p = 0.05$) between the occlusion conditions for the two vibrating proprioceptive-tactual warning signals (tactual signals 1 and 2).

Fig. 12 shows the response time to the different warning signals.
Again, this diagram indicates the significant effect of the different warning signals ($p < 0.01$). This effect can be explained mainly by the short response time to the steady force warning signal (tactual signal 3). The results of the ANOVA also show an almost significant interaction effect of the factors warning signal and occlusion ($p = 0.06$), see Fig. 13. Occlusion tends to give the largest differences in response for the two vibrating proprioceptive-tactual warning signals (tactual signals 1 and 2).

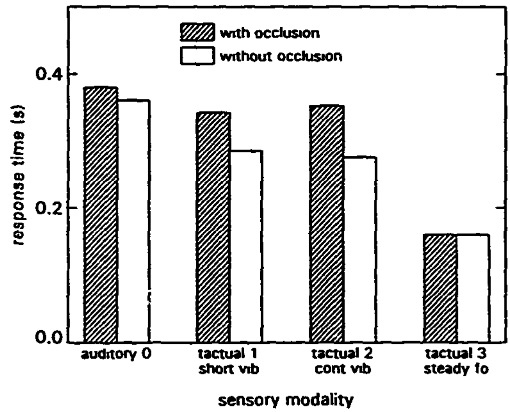

Fig. 13 Response time to the different warning signals, with and without occlusion.

3.2 Block II: Longitudinal control task

The ANOVA reveals a significant effect of accelerator characteristics ($p < 0.01$) indicating that the speed dependent accelerator configuration (act 1) leads to the smallest speed error. Fig. 14 presents the algebraic speed errors at location B and C. This figure also shows that in most cases speed is slightly too low as compared to the goal speed.

Absolute speed errors are given in Fig. 15. At location B absolute errors are the smallest ($p < 0.01$) for pedal configuration act 1 and act 3, which points to the efficiency in terms of speed error depending force (act 1) or location cuing (act

3). Keeping the correct speed between location B and C is not supported by configuration act 3, whereas configuration act 1 helps the driver to reduce the speed errors in this area as well. As a consequence the speed dependent feedback of configuration act 1 leads to the smallest speed errors at location C.

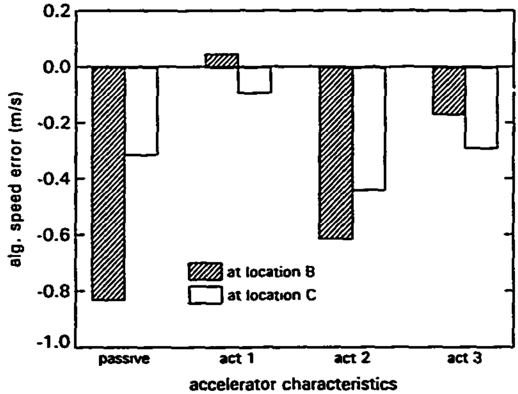

Fig. 14 Algebraic error in driving speed at locations B and C for the different accelerator configurations.

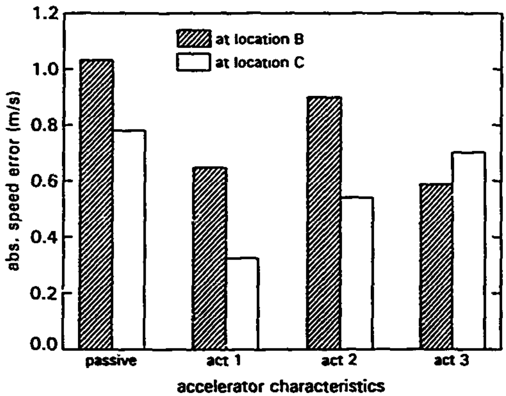

Fig. 15 Absolute error in driving speed at locations B and C for the different accelerator configurations.

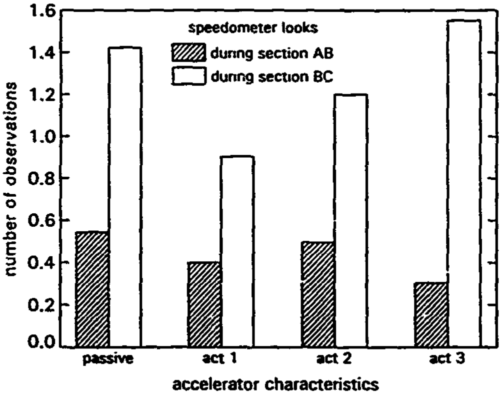

Fig. 16 Number of speedometer observations at the sections AB and BC for the different accelerator configurations.

Results on driver looking behaviour at the speedometer are shown in Fig. 16. Configuration act 3 informs the driver about where to release the gas-pedal, in which case hardly any speedometer observations are needed. Here also the supportive characteristics of configuration act 1 tends to be most efficient in section BC ($p = 0.09$). At this section configuration act 3 requires most observations whereas the permanent speed error feedback of configuration act 1 allows the driver to keep the number of speedometer observations low.

3.3 Block III: Combined control task

Considering the dependent variables related to speed control, the results correspond well with those from block II.
The results from block II compared with block III are summarized in Table IV.

Table IV Comparison of dependent variables block III with block II (two-tailed t-test, critical t-value = 2.18, $p = 0.05$, $df = 12$).

	mean II	mean III	t-value	sig
algebraic error at B				
active 1	0.05	-0.06	0.51	n.s.
active 3	-0.17	-0.03	-1.25	n.s.
algebraic error at C				
active 1	-0.09	-0.09	0.01	n.s.
active 3	-0.29	-0.19	-0.80	n.s.
absolute error at B				
active 1	0.65	0.60	0.50	n.s.
active 3	0.59	0.47	1.34	n.s.
absolute error at C				
active 1	0.32	0.32	0.12	n.s.
active 3	0.70	0.67	0.17	n.s.
number of speedometer observ. between B and C				
active 1	0.94	1.05	-0.26	n.s.
active 3	1.56	1.38	0.39	n.s.

The ANOVA revealed no significant results for the following variables: algebraic speed error at B and at C, absolute speed error at B, number of speedometer observations between location B and C. As in block II, absolute speed error at C differs significantly ($p < 0.01$) for the configurations act 1 and act 3. In general it may be concluded that the combined use of active controls for longitudinal and lateral control did not result in negative interference effects on speed performance.

However, analyzing the dependent variables concerning lateral control reveals different results. Like in block I the ANOVA indicates no significant differences for most of the variables. As an example, Fig. 17 shows the minimal lateral distance to the center line for both blocks. Having a closer look at the interaction effects, however, a significant interaction of speed and feedback combination turns up. See Fig. 18.

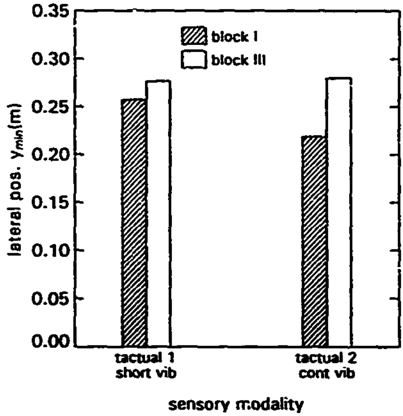

Fig. 17 Minimal lateral distance to the centre line, block I compared with block III.

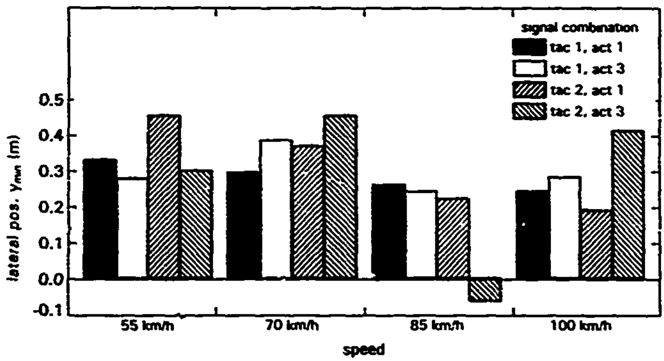

Fig. 18 Minimal lateral distance to the centre line; warning combination and speed.

For one warning signal combination (continuous vibrating steering wheel, short vibration via the gas pedal) and goal speed 35 km/h, even a negative lateral distance occurs, implying that the car actually passed the center line despite a steering wheel warning.

A closer look at this specific warning combination for the 85 km/h goal speed case shows, that this is the only speed condition where the gas-pedal vibration and the steering wheel vibration may coincide (see Table II; gas-pedal warning

4.1 s before B; at that time instant the continuous steering wheel vibration may still be active).
To get further insight in what happens with the steering wheel movements by the driver during the time the gas-pedal vibration is active, an additional dependent variable was derived from the steering wheel angle signals:

$|\dot{\delta}_s|_{2.6\text{-}3.6}$ mean absolute steering wheel velocity between time instant 2.6 (gas-pedal active 85 km/h case) and time instant 3.6 (a one second period was chosen to give the subject some time to react to the gas-pedal vibration).

The measuring period is comparable for all speed cases, since the lane-change manoeuvres always started seven seconds before B (see § 2.4.1).
Differences between conditions were tested for significance by way of an ANOVA (within-subjects design), which contained the following main factors: combined warning signals on two levels (only the warning combinations with the vibrating gas-pedal), occlusion on two levels, goal speed on four levels, and replica. This ANOVA revealed a significant effect of combined warning signals ($p < 0.05$) with a higher absolute steering wheel velocity for the continuous steering wheel signal (tactual signal 2, see Table I). There is also a speed effect ($p = 0.05$), with the highest absolute steering wheel velocity for the 85 km/h case.
These results indicate that the simultaneous occurrence of a vibrating gas-pedal warning and a vibrating steering-wheel signal may result in interference effects, which particularly influence steering behaviour. A continuous support via the gas-pedal (active pedal 1, see Table II) does not interfere at all with steering control actions.

4 DISCUSSION AND CONCLUSIONS

The results of block I support the hypothesis, that proprioceptive-tactual warning signals can be employed to interrupt an intended lane-change manoeuvre and to cause the driver to stay in the right lane. Steering of such a lane-change manoeuvre can be described in an open-loop control mode (see e.g. McRuer, Allen, Weir & Klein, 1977). The warning signals have been successful in breaking up this open-loop control mode and in transferring steering back to a closed-loop control mode, which should be further supported by visual stimuli. Comparison of proprioceptive-tactual warning signals with an auditory warning signal shows the effectiveness of those signals (see Fig. 10). The need for visual stimuli after the warning signal is clearly demonstrated by the large effect of occlusion on the minimal lateral distance to the center line (see Fig. 11). The significant effect of the steady force warning signal (tactual signal 3) can be explained by the omission of the reaction time to such a signal (see Fig. 12), since a direct and immediate intervention of the system (the active steering wheel) occurs which starts to turn the steering wheel into the right direction. The shorter

reaction times for the proprioceptive-tactual signals can also be explained in the sense of a stimulus-response compatibility or a so-called "perception-action" linking.

Choosing the most appropriate proprioceptive-tactual warning signal should stay open at this stage of research, since there might be different situations during lateral control to employ such signals. An example might be curve driving, where proprioceptive-tactual signals may be implemented to support and to correct closed-loop steering. A steady force warning via an active steering wheel into the appropriate direction might be the most informative signal in such circumstances, whereas in the case of breaking up an open-loop control mode a short vibrating proprioceptive-tactual warning signal can be - as the results show - an appropriate choice.

The results of block II show that "intelligent" force feedback via the accelerator may serve as an useful way to reduce speed errors. Comparing the different acceleration configurations considered in this study, it appears that force feedback related to some speed error criterion (configuration 1) leads to the lowest speed errors. Moreover, the results of driver speedometer observations indicate that this type of control support may also affect looking behaviour. This finding confirms the idea that force feedback from the accelerator may improve the quality of the driver-car interface from a workload point of view.

The results of block III show that in most cases the combined use of both accelerator and steering-wheel feedback may serve as an appropriate warning system. However, the simultaneous presentation of vibrating signals resulted in interference effects. The relatively large lateral position error in this situation suggests that the lateral control task is temporarily disturbed during the period of accelerator feedback. This finding should be considered as a preliminary result which requires further research.

Regarding the ultimate effectiveness of active control devices as suggested in this study a number of additional aspects has to be considered.
First, it is important that such support elements form a part of an integrated system which involves speed support, lateral control support, headway and anti-collision support (see Janssen & Nilsson, 1991) and cruise control options.
Second, it should be noted that until now the number of field trials carried out in this research area is very low. Therefore in addition to the simulator studies carried out thus far "real world" experiments in intelligent instrumented cars and small fleets are needed to evaluate the ultimate behavioral consequences of active support systems as suggested in this report.

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

The present study deals with the question whether at the handling level of car driving active control devices (i.e. active steering wheel, active gas-pedal) may serve as a part of an integrated, intelligent co-driver system, that may help the driver to behave safely and efficiently in tomorrow's traffic.
The experiment, which was carried out in the TNO driving simulator was devided into three blocks:

- a lateral control task (lane-change manoeuvre) supported by the active steering wheel,
- a longitudinal control task (speed control) supported by the active gas-pedal,
- a combined control task (lane-change manoeuvre and speed control) supported by both active controls.

Different force feedback characteristics for the active control devices served as the main independent variable. The results indicate that steering support may be fruitfully applied as a warning system preventing drivers to leave their lane. Furthermore, intelligent force feedback from the accelerator pedal appeared to be useful in speed-error reduction. Continuous force changes which are directly related to speed error seem most promising. Interference effects may occur in case of simultaneous presentation of vibrating signals on both steering wheel and accelerator. The present simulator findings need further verification in field studies.

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